Experimental Realization of a Localized One-Photon State

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(Received 16 September 1985)

In the process of spontaneous parametric down-conversion a signal and an idler photon are created simultaneously. By use of the photoelectric detection of the signal photon as a gate, a good approximation to the ideal localized one-photon state can be achieved. This has been confirmed by direct photon-counting measurements.

PACS numbers: 42.50.Bs, 32.80.−t, 33.80.−b

Fock states, or states with definite photon occupation number, form the most important basis for the representation of the quantized electromagnetic field. But despite the fact that processes giving rise to definite numbers of photons appear to be commonplace, a one-photon state in which the photon is localized is not easy to realize experimentally. For example, an isolated excited atom that behaves nearly as a two-level quantum system should give rise to a one-photon state in time, but the resulting photon would be distributed over all space. Moreover, a single atom is difficult to isolate, and if it is trapped in an optical cavity, the state of the field is never a true Fock state. On the other hand, in an atomic beam, and under most other experimental conditions, the number of atoms fluctuates, and the number of photons is then necessarily indefinite also, quite apart from the lack of localization.

Of course, a photon cannot be localized precisely in space and time,[1] but only within a certain region such that the linear dimensions of the region are large compared with the wavelength and the time interval is long compared with the optical period.[2,3] But that still leaves room for the position and time to be pretty well defined. We wish to report on a simple experiment in which a localized one-photon state is achievable in a short time interval with good accuracy, as confirmed by direct photoelectric counting. The experiment is based on the phenomenon of spontaneous parametric down-conversion, in which a coherent beam of light, the pump beam, incident on a crystal lacking inversion symmetry, results in the fission of some incoming photons into two lower-frequency signal and idler photons. The effect has long been known,[4] and has been observed both with light[5,6] and with x rays.[7,8] We have recently demonstrated that the two down-converted photons are simultaneous to better than 100 psec,[9] which is substantially less than the transit time of the light through the crystal or the coherence time of the incident pump beam. It follows that if a signal photon is detected at some position within some short time interval T, then there exists a conjugate idler photon in a one-photon state at a corresponding position at the same time. As T can be very short, the chance appearance of an unrelated photon within T can be made very small.

Figure 1 shows an outline of the apparatus, which is rather similar to that used in the earlier experiments,[9,10] except for the counting electronics. A light beam from an argon-ion laser oscillating in the uv at 351.1 nm is allowed to pass through an 8-cm-long crystal of potassium dihydrogen phosphate, whose optic axis makes a 50.03° angle with the normal to the crystal face. The down-converted signal and idler photons, which emerge in cones centered on the laser beam, are collected by lenses and directed through interference filters centered at the approximate conjugate signal and idler wavelengths 746 nm and 659 nm to two counting photomultipliers A and B (A is an RCA C31034, while B is a Hamamatsu R1645 microchannel plate detec-

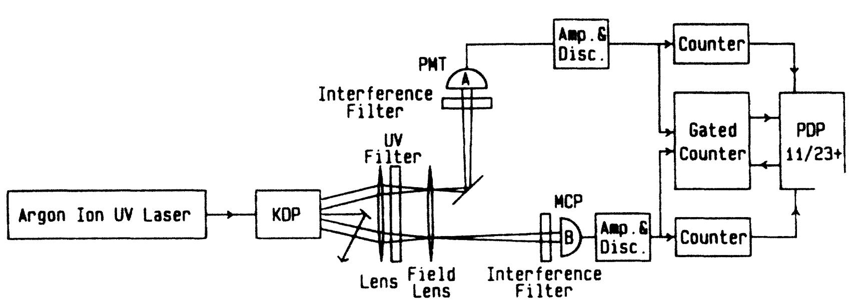

FIG. 1. Outline of the apparatus.

tor). The microchannel plate detector has rise times and intrinsic transit-time spreads of about 150 psec. The pulses from detector B are fed to a fast amplifier and discriminator and then to a scaler with 3-nsec pulse-pair resolution, where the idler photons are counted. Counter B is gated on by the pulse derived from detector A, which receives the signal photon, for a counting time interval $T \approx 20$ nsec. At the end of the counting period T, the number m of detected photons is transferred to the computer memory, and the counter is cleared and reset for the next counting cycle. If the number m occurs $N(m)$ times in N cycles, then the counting probability $P(m) = N(m)/N$. The average counting rates for the detectors were $R_A = 2609.3$/sec and $R_B = 3913.5$/sec, and the corresponding background rates in the absence of any down-conversion were $r_A = 554.0$/sec and $r_B = 460.2$/sec. The probability θ that a count in channel A was initiated by a signal photon is therefore $\theta = 2055.3/2609.3 = 0.79$.

In the absence of dark current or undesired background photons, and with perfect collection efficiency and perfect detectors, the probability $P(n)$ of detecting n idler photons in the short counting interval T initiated by a signal photon would be very nearly $P(n) = \delta_{n1}$. But because each conjugate idler photon has only a small probability η of being registered, most counting intervals result in zero counts. In general, the probability $P(m)$ of registering m counts is given by a convolution of the probability $p(n)$ that n idler photons are produced with a Bernoulli distribution,

$$P(m) = \sum_{n=m}^{\infty} p(n) \binom{m}{n} \eta^m (1-\eta)^{n-m} = \eta^m \sum_{s=0} \frac{(m+1)^{(s)}}{s!} (1-\eta)^s p(m+s), \tag{1}$$

where $m^{(r)} = m(m+1)(m+2)\ldots(m+r-1)$.

In the presence of background counts from light other than conjugate idler photons and/or dark current in channel B this formula has to be modified somewhat. If $p_b(n)$ is the probability that n background counts are registered during the counting interval T, then

$$P(m) = \sum_{r=0}^{m} p_b(r) \sum_{n=m-r}^{\infty} p(n) \binom{n}{m-r} \eta^{m-r} (1-\eta)^{n-m+r} = \sum_{r=0}^{m} p_b(r) \eta^{m-r} \sum_{s=0}^{\infty} \frac{(m-r+1)^{(s)}}{s!} (1-\eta)^s p(m-r+s). \tag{2}$$

Both probabilities $P(n)$ and $p(n)$ must be understood as conditioned on the appearance of a count in channel A. The background probability $p_b(n)$ can be measured directly with a random background of the same average intensity. It is quite well approximated by a Poisson distribution. η is given by the product of the quantum efficiency α_B of detector B and the conditional probability β_B that whenever a signal photon is registered by detector A the conjugate idler photon reaches detector B. If the collection aperture at detector B is large enough to ensure that all photons conjugate to the signal photons are collected, then β_B is determined by the transmissivities $T_A(\omega)$, $T_B(\omega)$, and T of the two interference filters and of the remaining optical system, and is given by

$$\beta_B = T \int_0^{\omega_0} T_A(\omega) T_B(\omega_0 - \omega) d\omega \Big/ \int_0^{\infty} T_A(\omega) d\omega, \tag{3}$$

where ω_0 is the pump frequency. T is found to be 0.30 by direct measurement. From Eq. (3) and the transmissivity curves for the interference filters we find that $\beta_B \approx 0.30 \times 0.34 \approx 0.10$. The quantum efficiency α_B was determined by direct measurement at a wavelength of 632.8 nm, and the value at 659 nm was estimated from the frequency response of the photocathode. This leads to $\alpha_2 \approx 0.027$, and $\eta = \alpha_B \beta_B \approx 0.0027 \pm 10\%$.

In principle, $p(n)$ can now be derived from measurements of the probability $P(m)$ with the help of Eq. (2). We shall not go into the general problem of inverting Eq. (2). However, in the special case in which $P(m)$ is negligi-

TABLE I. Measured photon-counting distributions.

Observed data	Counting probabilities	Background probabilities	Derived photon probabilities
$N = 6\,000\,000$			
$N(0) = 5\,985\,901$	$P(0) = N(0)/N = 0.997\,65$	$p_b(0) \approx 1$	$p(0) \approx -0.17$ to 0.04
$N(1) = 14\,098$	$P(1) = N(1)/N = 0.002\,35$	$p_b(1) \approx 8.8 \times 10^{-5}$	$p(1) \approx 1.06 \pm 10\%$
$N(2) = 1$	$P(2) = N(2)/N < 10^{-6}$	$p_b(2) \approx 0$	$p(2) \approx 0$

bly small for $m \geq M$ ($M = 2, 2, 4, \ldots$), which implies that $p(n) \approx 0$ for $n \geq M$ also, Eq. (2) results in M linear equations in the M unknowns $p(0)$, $p(1), \ldots, p(M-1)$, which can be solved. In particular, when $M = 2$, $p(1)$ and $p(0)$ are the only unknowns. If $\theta = (R_A - r_A)/R_A$ is the probability that a given count in channel A was initiated by a signal photon, then from Eq. (2) the probability $p(1)$, conditional on a signal photon, is given by

$$p(1) = [P(1)p_b(0) - P(0)p_b(1)]/\theta\eta p_b^2(0). \quad (4)$$

The results of measurements of the photoelectric counting distribution $N(m)$, the probabilities $P(m)$, and the background probability $p_b(m)$ are given in Table I. The number of counting cycles was $N = 6 \times 10^6$ and the probabilities are negligibly small for $m \geq 2$. No correction for the 3-nsec dead time following each count was made, but at the low counting rates of the experiment such corrections would be very small.

We first note that the observed number of single counts $N(1)$ is substantially greater than the number NR_BT expected for random, uncorrelated events, whereas the observed number $N(2)$ is very much less than $N^2(1)/2N$. The detected photons are therefore far from random. The photon distribution $p(n)$ derived from $P(m)$ by use of Eq. (4) is also given in Table I and is shown in Fig. 2. The values of $p(1)$ and $P(0)$ have been truncated above 1 and below 0. It will be seen that we have a close approximation to the localized one-photon state. The uncertainties come largely from the uncertain value of η. We point out that although one-photon states can also be realized in other circumstances, such as a cascaded two-photon emission process,[11,12] the photons in that case are not localized in the same sense as here. Even a perfect detector triggered by the first photon would not result in the probability $p(n) = \delta_{n1}$ for the second photon.

Another useful indicator of a number state is based on the parameter[13]

$$q = [\langle (\Delta n)^2 \rangle - \langle n \rangle]/\langle n \rangle, \quad (5)$$

which is negative whenever the statistics are sub-Poissonian, and takes the value $q = -1$ for a pure number state. Even for the raw uncorrected data shown in column 2 of Table I we find sub-Poisson statistics with $q \approx -0.0024$. But from the derived photon probability distribution $p(n)$ we obtain $q \approx -1.06 \pm 10\%$ which again indicates that we are close to the ideal one-photon state.

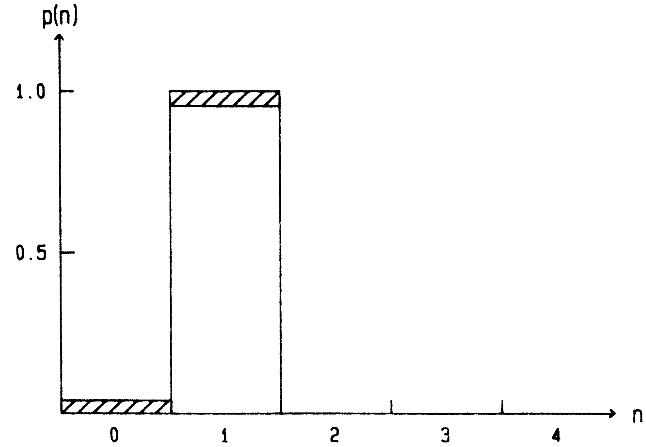

FIG. 2. The derived photon probability $p(n)$ conditioned on the detection of a signal photon. The cross-hatched regions indicate the uncertainties of $p(n)$.

This work was supported by the National Science Foundation and by the U. S. Office of Naval Research.

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